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DETECTION AND REMOVAL OF DEFECTS IN APPAREL PRODUCTION

By
Wayne Tincher, Wayne Daley and Wiley Holcombe

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W. Tincher, W. Daley and W. Holcombe

Georgia Institute of Technology
Atlanta, Georgia 30332

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Defense Logistics Agency
DMERO
Cameron Station
Alexandria, VA 22304

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A workstation utilizing machine vision has been designed and constructed to detect and remove defective cut-parts prior to initiation of the assembly operations. The workstation employs two vision systems --an area camera and a line camera--to inspect parts on a conveyor belt both statically and dynamically. The color of the parts is also determined and the area and perimeter are measured to detect improperly cut parts. The acceptable parts are then stacked in a manner suitable for input to an automated sewing station.

The workstation should permit placing into the assembly operations a set of defect free, properly cut and color matched parts. It is estimated that this cut-part inspection system will reduce defects in finished garments by approximately 50% and should greatly simplify the labor intensive and costly fabric defect control systems currently in place in most apparel plants.

The completed cut-part inspection workstation was demonstrated at the DLA Apparel Manufacturing Technology Center at Southern College of Technology.

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Wayne Tincher, Wayne Daley and Wiley Holcombe
Georgia Institute of Technology
Atlanta, GA 30332

ABSTRACT

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Georgia Institute of Technology
Atlanta, Georgia 30332

I. INTRODUCTION

Fabric defects are a constant and continuing problem in the manufacture of apparel. Despite major improvements in yarn manufacturing equipment and knitting and weaving machines, it is not possible at the present time to manufacture defect free fabric. In an era when "zero defects" is the goal of most textile mills, it must be admitted that this still remains a goal and not an accomplished objective.

Defects in fabric create significant problems for the apparel manufacturer and a variety of systems have been developed to cope with the defect problem. Some firms conduct 100% inspection of in-coming fabric, mark or label detected defects and attempt to remove all fabric defects in spreading. Other firms depend on inspection during spreading by the spreader operator and the removal of the detected defects prior to cutting. A few firms depend on sewing operators to detect flaws in cut parts and to replace the parts before manufacturing proceeds. Still others make no attempt to find fabric defects during manufacturing, but rely on final garment inspection to detect and remove defect containing garments. In a few cases, cut parts are examined individually before bundling and defective parts are replaced prior to initiation of the sewing operations [1].

All these methods of coping with fabric defects are costly and disruptive in the apparel manufacturing process and most are not successful in eliminating fabric defects in finished garments. Therefore, fabric defects are a major point of conflict at the textile and apparel industries interface. Study of this problem has been the subject of continuing investigation in the military procurement system but no satisfactory solution is apparent [2-4].

The problem of detecting and removing fabric defects increases in severity as more apparel operations are automated. Automated spreading machines requiring less worker attention reduce the probability of finding defects and, in some cases, of finding markers that have been placed on the fabric denoting the location of defects. With fewer workers handling parts in sewing operations, the probability that a defect will be detected decreases.

Most of the effort at the present time in automatic detection of defects in fabric is directed toward inspection of fabric rolls. A number of companies either have, or will market in the near future, systems for automatic roll inspection [5]. The unfortunate disadvantage of these systems is that if defects are detected they can only be marked (or cut out and replaced by a seam which is another defect). The defect must still be removed with the fabric loss and time loss involved in such defect removal. The approach taken in this work is to develop systems to automatically inspect cut parts and only remove those parts from the production process which are defective. This approach should significantly reduce the fabric loss due to defects and should decrease the number of fabric defects that go through the entire assembly process and result in garment seconds.

II. THE COST OF FABRIC DEFECTS

Research efforts in the apparel quality area would benefit greatly from a more detailed data base on defects at various stages of manufacture and the economic impact of defect detection and removal at these various stages. Most of the data on apparel defects that have been published report only defects in finished garments. This information is useful but it does not account for the many inspection steps during textile and apparel production and the difficulties and costs of removal of defects at many points in the production process. At the present time, it is difficult to evaluate the total economic impact of new defect detection technologies due to the absence of good baseline cost data for existing procedures for defect detection and removal.

Some estimates of the cost of fabric defects in apparel production were collected a few years ago from a cross-section of apparel manufacturers [1]. The results are shown in Table 1.

FIRM TYPE	INSPECTION COST	FINISHED GARMENTS SECONDS	SECONDS COST	% OF GROSS
Jeans	$ 135,000	0.8%	$660,000	0.30%
Men's Shirts	$ 33,000	1.0%	$326,000	0.33%
Lingerie	$ 400,000	----	----	0.29%
Children's	$ 16,000	0.4%	$ 16,000	0.39%
Men's Suits	$ 75,000	----	----	0.38%
Sportswear	$ 19,000	0.4%	$ 59,000	0.17%
Men's Formal	$ 60,000	----	----	0.28%

Table 1 Cost of fabric defects in apparel manufacturing.

Two of the companies (Men's Suits and Men's Formal Wear) attempted to find and remove or correct all fabric defects during assembly of the garments. They estimated the costs for these efforts at $78,500 and $50,000 respectively. The results in Table 1 certainly suggest that the total cost of fabric defects to the apparel industry is approximately 0.3% of total gross sales. In terms of the industry wholesale volume in 1980 when the study was conducted, the total dollar cost of fabric defects to the apparel industry would have been in excess of $100,000,000.

Some more recent studies on the impact of fabric defects on finished garment quality have been conducted on military garments. In a study of 25 Battle Dress Uniform (BDU) coats and trousers, a total of 310 defect points were assessed on inspection. Of the 310, 159 or 51% were fabric defect points [6].

In a later study of some 8000 finished military garments [7], 85% of the quality problems were textile (i.e. fabric) related. The single most common cause of non conformance was fabric shading (38%) in garment parts.

The Apparel Research Committee in conjunction with the Apparel Quality Committee of the American Apparel Manufacturers Association recently undertook a survey of apparel manufacturers to identify the most common and the most damaging defects in finished garments [8]. Visual defects in fabric were by far both the most common and the most damaging of the defects listed. Shading was number 4 on the list of most damaging defects and number 7 on the list of most common defects.

As part of the current research program, a survey of defects in finished garments for a period of one year in 20 plants manufacturing approximately 20 million pair of denim jeans was obtained. The data show that 1.15% of all finished garments were classified as irregulars due to fabric defects.

One of the more common approaches to elimination of fabric defects in finished apparel relies on detection and removal of defects during spreading of the fabric for cutting. In many cases the fabric will have been inspected by the fabric manufacturer and the defects marked in some manner. The defect markers are detected either automatically or by the spreader operator and the defects removed. In other cases the spreader operator will inspect the fabric as it is being spread and remove any defects he finds. This method of defect elimination results in loss of significant fabric for each defect as the ply can only be cut at specific locations to prevent the cut from crossing one of the garment parts. One study has been reported in the United Kingdom on the cost of fabric defect removal in spreading [5]. This study found that in a large apparel plant, an average of 1,575 fabric flaws were detected per day and that three-quarters of a yard of fabric was lost for each defect removed in the spreading operation. It further suggested that the time required for removing defects was a substantial contribution to the overall spreading time.

As part of the current project, similar data have been collected on the losses due to removal of fabric defects in spreading of denim for jeans manufacture. In this study involving spreading of over 7000 yards of fabric, 86 defects were removed with a total loss of 98.8 yards of fabric. This represents a loss of 1.1 yards per defect or 1.4 % of the total yardage being spread. The actual time loss due to cutting and removal of defects was over 35 minutes or 5.8% of the total time required to spread the fabric (the actual time credited to the spreader for defect cutting was 14.2%). It was also apparent in observing this operation that not all marked defects were detected and removed by the spreader. Thus, significant losses in time, material, and seconds are being experienced by the companies in the apparel industry using this approach to fabric defect removal.

The importance of early detection and removal of fabric defects was emphasized in a recent report on the cost of removal of fabric defects at various stages in the manufacture of high fashion jeans. The following costs for correcting of a single fabric defect during various apparel manufacturing steps were reported [9]:

Spreading/Cutting	$ 0.60
During Sewing	$ 12.00
Sewing Completed	$ 23.00
Finishing Completed	$ 32.00
Retail Return	$ 72.00

This study clearly demonstrates the economic importance of detection and removal of fabric defects prior to the beginning of the sewing operations.

The existing data clearly indicate that roughly 1% of all manufactured apparel must be classified as off-quality due to fabric defects. This level seems to persist over at least the last decade despite improvements in fabric manufacturing, extensive inspection of fabric rolls, emphasis on quality assurance programs and intensive efforts to find and eliminate fabric defects in the garment manufacturing process. The available data strongly suggest that defects in fabric are a major and very costly problem in apparel manufacturing and that new techniques and procedures are clearly needed to address this problem.

III. AN AUTOMATIC DEFECT DETECTION SYSTEM

Since fabric is produced and handled in continuous rolls prior to the cutting operation, the only action on defects than can be taken before cutting is to mark defects. Removal must be postponed to the spreading operation or later since removal of defects from continuous rolls either requires seaming (an additional defect) or production of smaller rolls which greatly reduces the efficiency of fabric spreading and utilization. The losses that can be expected by removal of defects in spreading have been detailed above.

The current work is based on the assumption that the ideal solution for the problem of eliminating fabric defects would be the removal of cut parts that contain defects immediately after the cutting operation. Such an approach should significantly reduce the fabric loss due to defect removal since only those parts that contain defects that will be visible in finished garments need be removed. Defects that happen to fall in waste areas of the marker or that occur in nonvisible parts of the garment would not require removal. Instead of losing over one yard of full width fabric per defect when defects are removed before cutting, only the actual fabric in the defective part would be lost.

Some apparel plants practice manual inspection of cut parts and removal of parts containing defects as a method of coping with the fabric defect problem. A limited observation on the effectiveness of this technique suggests that it is quite effective in elimination of fabric defects in finished apparel [1]. Of course manual inspection of cut parts is very labor intensive and costly. However, the very significant advances in, and cost reduction of, machine vision systems in the recent past suggested that the cut part inspection and removal of fabric defects could be automated.

A fabric defect detection workstation was designed, therefore, for automatic inspection of cut parts. The workstation consists of five components--a pick and place device to select parts from a stack and place them individually on a conveyor belt, a conveyer belt transport system to move parts to the various inspection stations, a machine vision system (including both line and area camera systems) to inspect parts for fabric defects, a non contact color measurement system to precisely measure the color of each part, and a take-off device that will reject defective parts and place acceptable parts in a configuration suitable for input to an automated sewing workstation. The system will be under the overall control of a microcomputer for integration of the operation of the various components in the system and for analysis of the collected data to permit decisions regarding the acceptability of each part. The system can also calculate the area and perimeter of each part to determine if the part has been properly cut. Thus, the workstation should insure that only defect free, color matched, and properly cut parts will enter the assembly operations with the parts already configured to feed an automated sewing workstation.

Denim fabric used for manufacture of Navy Men's Utility Trousers was selected for demonstration of the cut part inspection system. The manufacturing process for this product is typical of the very large segment of the apparel industry involved in production of denim garments. The Navy trouser has eleven parts (left and right front and back leg panels, 4 patch pockets, left and right fly, waistband). The prototype workstation was designed to inspect the leg panels and the pockets. The design objectives were an inspection time of 4 seconds for a leg panel and 1 second for a pocket (approximately 20 seconds inspection time per garment) with a positive detection of over 50% of the most common defects found in denim fabric. The goal of the inspection workstation was a minimum of a 50% reduction in seconds in finished garments due to fabric defects and shading problems. It was felt that such a workstation would make a very attractive contribution to reduction of costs due to fabric defects in finished garments.

Equipment selected for initial study and evaluation and possible inclusion in the proof-of-concept model of the workstation is shown in Table 2.

Part Pick-and-Place	Jet Sew
Machine Vision Unit	IRI SVP Area Camera
	Digital Design Line Camera
Color Measurement	Hunter SpectraProbe
Conveyor System	In-house Design
Take-off Unit	In-house Design

Table 2 Cut part inspection unit components.

A primary consideration in equipment selection was the time constraints imposed for the part inspection. For example, the Hunter SpectraProbe was the only non contact color measuring instrument capable of a complete color measurement in less than 1 second.

IV. DEFECTS SELECTED FOR STUDY

It has been reported that approximately seventy different flaws have been identified in denim fabric [10]. Fortunately, many of these defects are very uncommon. To achieve some idea of the number and frequency of defects that currently appear in denim, approximately 7000 yards of denim were inspected and some 100 defects were removed for study. Fifty-four of these were identified by comparison with defects catalogued in the Manual of Standard Fabric Defects in the Textile Industry [11] or by experts in the analysis of fabric defects (many of the defects common to more recent shuttleless weaving machines are not listed in the Manual). The fifty-four defects are listed in Appendix A.

As indicated in Appendix A, the fifty-four defects were of 14 types with five defects accounting for 65% of the observed flaws. These 14 defect types served as the test set of defects for development of machine vision systems.

V. AUTOMATIC DEFECT DETECTION

A. Lighting and Optics Design

In designing any machine vision solution, two areas of great importance are those of lighting and optics. Attention to these aspects of a design can sometimes mean the difference between success and failure. It was decided therefore to do a preliminary study of these parameters to determine the lighting and optical configuration most suitable for application to fabric defect detection.

In acquiring a camera image the properties of various parts of the system interact to determine the final quality of the image. Some of these characteristics include the light source, the properties of the material being illuminated, as well as the properties of the sensors in the cameras. To determine the overall effect of these interactions, experiments were conducted using different light sources and configurations. The aim of the experiments was to find the optimum configuration(s) for conducting automated inspection.

For the tests, the orientations illustrated in Figures 1, 2 and 3 were used. These schemes are in general called direct lighting configurations and the aim is to identify any directional property of the material that could be utilized to enhance the contrast between acceptable and defective portions of the material. Different light sources were also used to span the wavelength range from the ultraviolet to the infrared (this includes the visible spectrum).

The tests were carried out by making reflectance measurements in the orientations shown in Figures 1, 2 and 3, using five different light sources (incandescent, fluorescent, halogen, orange halogen, ultraviolet). This was done using a spectroradiometer. A white Teflon block was used as a reference standard and its reflectance was taken as the 100% reflectance in each of the experimental orientations with the different light sources. The reflectance of normal denim and of denim exhibiting 3 different types of defects with a range of visual reflectance properties (accumulator defects, dye streaks, oil spots) were obtained relative to the Teflon block reflectance. The relative reflectance intensity differences between acceptable and defective segments of the material were then tabulated with each of the five light sources in each of the three configurations. In addition, regions in the electromagnetic spectrum that showed noticeable contrast were also noted.

These data were tabulated and an ANOVA procedure used to aid in the analysis. The data indicate that orientation is a significant factor in determining contrast differences with the orientation shown in Figure 1 being the most significant. As would also be expected the type of defect being examined has a significant effect on the contrast differences.

Later work with the configuration shown in Figure 1 on a larger selection of defects revealed that this configuration yielded very large differences in reflectance with defects in the warp and fill directions. The geometrical arrangement that was ultimately selected employed illumination of the sample with two light sources impinging on the fabric at 45 degree angles in a plane along the long axis of the conveyor belt with observation by the camera at 0 degrees (perpendicular to the fabric). This optical arrangement was used in all additional studies and was employed in the proof-of-concept workstation.

The incandescent and halogen light sources produced the greatest contrasts between normal and defective fabric in the designed experiment. Two Newport Model MP-1000 lamps in the configuration described above were therefore selected for all later experiments with the machine vision system.

B. Development of Machine Vision Systems

From a machine vision viewpoint the defects present in denim can be placed into two broad classes. These would be defects that show up as contrast differences and defects that materialize as changes in a regular pattern. Methods for defect detection were examined using both the area and line cameras. Area cameras are cameras whose sensor elements are arranged in a matrix while line cameras are cameras whose sensor elements are arranged linearly.

1. Area Scan System Results

There are two fairly effective methods for use in detecting defects in denim material involving the use of an area vision system and some form of uniform lighting. There are however several drawbacks with each of these methods. What follows is a brief description of what was found to be helpful and some of the problems encountered in the pursuit of a denim detection system with an area vision system.

The two methods, to be called **Dyadic Analysis** and **Subtractive Analysis** for the duration of this report, involve performing a dyadic operation on a grayscale image and the Subtractive Analysis involved subtracting a grayscale image from an average image of what is considered to be good denim respectively. Each is outlined in some detail below.

The Dyadic Analysis involves acquiring a full grayscale image of the area to be inspected, "running" this image through a series of convolutions to "smooth" the image out and then performing a dyadic operation on the image. During the dyadic operation every pixel that is not within a predetermined intensity band is considered to be a defective area and therefore highlighted. All other areas, ones whose intensities fall within this predetermined band, are considered to be part of normal denim material and made dark. At present the cutoff band is considered to be the average grayscale of a good piece of denim minus twice the standard deviation and the average plus twice the standard deviation. This band has proven to highlight a majority of the supplied defects and has therefore not been changed.

The Subtractive Analysis technique involves subtracting a grayscale image from an average image of what is considered to be good fabric. The result of this image is then run through a binarization process where any pixel above a set grayscale is considered to be a defect. This threshold was found by examining several histograms of defective as well as good fabric and determining a point at which all good denim disappears and defective denim remains. This method has done well in finding all defects that cause light spots in the denim material.

In viewing the histograms of denim samples that were subtracted from an average image of what was considered to be good denim, an optimum resolution of 42 pixels per inch was found. At this resolution there is a noticeable separation between good fabric samples and bad fabric samples and samples having any histogram data above the middle light intensity (128) are considered to be bad denim. Optimum resolution was determined using a simple version of Subtractive Analysis because this method is largely dependent on the resolution of the grayscale image.

This number was found by viewing histograms of what is considered to be good denim and a few samples of bad denim at various resolutions and attempting to determine a threshold point above which only bad denim shows data. The above mentioned optimum resolution of 42 pixels per inch was the point at which this separation is most evident.

Typical sizes observed for a selection of denim fabric defects ranged from 0.015 to 0.054 inches. As a reference, the smallest defect detectable, and also the average size of a light spot across what is considered to be good denim, is taken to be .012 inches. According to this data, the maximum defect size to be detected with the provided samples at the selected resolution is between 2 and 3 pixels in size.

SAMPLE NUMBER	DEFECT TYPE	DETECTION SA	DETECTION DA
518441-3	Slub	X	X
525579-2	Slack Filling	X	X
525123-1	Slack Warp		X
525579-1	Woven in Waste		X
523080-1	End Out (Wrap)		
516223-1	Sloughed Filling	X	X
518441-2	Broken Pick	X	X
516223-2	Dyeing Defect	X	X
521692-2o	Finishing Spot		
519551-5	Oil Spot		
520438-10	Harness Breakdown		
513788-4	Jerked In Filling	X	X
SA -- Subtractive Analysis			
DA -- Dyadic Analysis			
X -- Indicates defect was found			

Table 3 Area camera defect detection effectiveness.

When tested with a group of denim fabrics that contained one example of each type of defect, it was found that for the defects that caused light areas, the Dyadic Analysis method proved to be more effective than the Subtractive Analysis. According to the results shown in Table 3, the Dyadic Analysis method found 62% of the defects examined and the Subtractive Analysis found 46% of the defects. Both methods, however, proved to be useless for defects that caused dark spots on the fabric. The Subtractive Analysis method tends to make the dark area the same color as what is considered to be good denim and the dark defective areas fall within the preset band of the Dyadic Analysis method. With all the defects in the test group, both methods found the reported light defects each time the test was run.

2. Line Scan System Results

A major technique employed in detection of defects using a line scan camera is thresholding. In thresholding, a simple upper and lower intensity threshold pair are used to detect significant transitions in intensity outside of the allowable bounds. The optimum threshold levels for denim were determined by studying normal fabric samples and determining their intensity variations. The thresholds were then set just above and below the upper and lower bounds. However, the rate of defect detection afforded by this method was not satisfactory due to its inability to differentiate between several defects and normal fabric. It became apparent that a higher contrast between warp and fill should be attempted and some type of pattern recognition should be implemented.

The first requirement was satisfied with the use of a narrow bandpass filter centered at a 600 manometer wavelength. The second requirement was dealt with by developing a new method of defect detection utilizing a combination of different tests in combination with two thresholds positioned above the average image. In addition to calculating potential intensity variations in normal fabric, observations had to be made relative to the size and shape of each defect type to be analyzed. Characteristics such as average defect intensity must also be taken into account. Once these determinations have been made and the thresholds set, the lower threshold is used to detect increased activity in a specified frequency range, while the upper threshold keeps track of peaks in intensity. The information gathered on the size and shape of each defect type was incorporated into the new defect detection program algorithms and used in conjunction with the thresholds to determine defect occurrences. An average intensity for normal fabric was also measured, and compared against test fabric to identify certain defects.

The method used to determine the upper and lower threshold settings is not yet an exact one, and relies on a trial-and-error method to determine the optimum settings. Keeping in mind the fact that it is required to locate ranges of intensities where a maximum of change between normal and defective material is occurring, several samples of normal and defective material are observed, and each threshold is set to identify an area of maximum change. Currently, the lower threshold is set at seven intensity levels above the reference image and the upper threshold is set at 23 intensity levels above the reference image.

To illustrate the implementation of the previously described algorithm, Figures 4 and 5 show representations of normal and defective fabric line scans, respectively. In the case of the defect pictured in Figure 5, all points above the upper threshold are counted from left to right.

When 15 pixels are found above the threshold, or 4 consecutive upper threshold transitions are detected and 10 pixels are found above the threshold, a defect is identified. Figure 4 does not exhibit either of these characteristics and is correctly identified as normal fabric. In addition, the lower threshold identifies transitions of 20 pixels or more, or seven consecutive transitions as defects. Finally, the total intensity variation across the scan line is calculated and compared to a reference value to identify more subtle defects.

DEFECT NAME	THRESHOLD SETTING	FALSE HITS	CORRECT HITS
Accum, Kinks	23,7,20	No	Yes
Oil Spot	23,7,20	Yes	No
Slack End	23,7,20	No	Yes
Seam	23,7,20	No	Yes
Harness Breakdown	23,7,20	No	Yes
Slack End	23,7,20	No	Yes
Jerked In Filling	23,7,20	No	Yes
Dyeing Defect	23,7,20	No	Yes
Slack End	23,7,20	No	No
Slub	23,7,20	No	Yes
End Out (Wrap)	23,7,20	No	Yes
Stub (Fill)	23,7,20	No	Yes
Broken Pick	23,7,20	No	Yes
Sloughed Filling	23,7,20	No	Yes
Dyeing Defect	23,7,20	No	Yes
Slack End	23,7,20	No	Yes
Slack End	23,7,20	No	No
Broken Pick	23,7,20	No	Yes
Slub	23,7,20	Yes	Yes
Slub (Wrap)	23,7,20	Yes	Yes
Slub	23,7,20	No	Yes
End Out	23,7,20	No	Yes
Oil Spot	23,7,20	Yes	No
Sloughed Filling	23,7,20	No	Yes
Harness Breakdown	23,7,20	Yes	Yes
Finishing Spot	23,7,20	No	Yes
End Out	23,7,20	No	Yes
Slack End	23,7,20	No	Yes
Woven Waste	23,7,20	No	Yes
Slack Filling	23,7,20	No	Yes

Table 4 Results of defect detection trial line scan camera.

Table 4 shows the results obtained in a detection test of 30 fabric defects where sample orientation and position were carefully controlled. The threshold settings listed represent upper threshold offset from average image, lower threshold offset, and required defect width. The threshold offset numbers are given in terms of intensity levels where the maximum level is 256, and the defect width is given in pixel widths.

Orientation can play a role when the defect in question is directed along a particular axis, such as the Sloughed Filling or Slack End defects. Because the line scan system is effectively one-dimensional, these defects may appear in certain orientations to be nothing more than normal fabric. Presently, each defect must be aligned to closely coincide with the orientation of the scan line in order to provide reliable detection. To overcome this limitation, a two-dimensional picture may need to be constructed by storing several successive line scans for periodic analysis or buffers might be maintained on several potential defects as each individual line is scanned.

The difference in average intensity does not vary significantly from one sample to another, but a few samples differ greatly from the norm and even the small differences between the majority of samples can pose a problem. All image analysis techniques require a defect-free reference image from which to set constraints, and consistency in overall intensity of any material being analyzed is crucial to the success of these techniques. It is assumed, however, that individual pieces put together into a single garment will be from the same roll number and sufficiently close in average gray-level intensity. Each piece can then be analyzed with the same threshold settings, except some of the more "noisy" ones, whose intensity levels tend to vary widely, even within the same sample. A low-pass filter may be required to adequately analyze these samples.

C. Other Techniques

Other possible techniques for defect detection were evaluated to determine their effectiveness for fabric defect detection. These included: texture, frequency spectrum analysis, and morphological filtering. The results of these investigations are described below.

1. Texture

The spatial gray level detection method [12] was chosen as a method of automatic texture discrimination. It works by finding the probability of going from any gray level to any other gray level in each of four directions, 0, 45, 90, and 135 degrees from the horizontal. A matrix is constructed for each direction using a normal sample of fabric and repeated for each defective sample being tested. Five texture feature formulas (energy, entropy, correlation, local homogeneity, and inertia) are calculated using the matrices and comparing normal and defective samples. As an example, three normal 32x32 pixel samples were analyzed along with one defective 32x32 sample. The resulting calculations showed no definite contrast between normal and defective samples, due to the fact that the formulas are designed for macroscopic differentiation rather than pixel-level detection as was the case here.

2. Frequency Spectrum

Frequency Spectrum Analysis was also studied. The Fast Fourier Transform (FFT) was investigated as a method of defect detection because of the characteristic periodicity of warp and fill used in the material being analyzed. It was thought that defects might show up well in a particular frequency range relating to this periodicity. With a few exceptions, however, this did not prove to be the case. There is no significant difference between the normal samples and most defective samples. This may have been due to insufficient resolution or lack of defect presence across the scan line. As a further attempt to establish a link between frequency data and defects, a sample of each half and each quarter scan line of the Endout, Harness Breakdown, and Slub defects were collected and compared against similar sections of normal material. It was thought that if a defect was more pronounced in a particular section of the scan line, it would be more effective to take several sections of the scan line and perform separate FFT's on each section. While the Slub defect showed up well as a smoothing of lower frequencies in section 1 of 2 and 2 of 4, neither the Endout nor Harness Breakdown showed any significant changes.

3. Morphological Techniques

The use of Morphology analysis in machine vision appeared to be well suited to the detection of a large number of typical defects which might occur in the manufacture of fabric. Mathematical Morphology employs two simple building blocks from which may be built a large number of transformational tools; these tools can then be used to manipulate an image of the test sample in a manner that can be dealt with by computer software to compare to a standard, defect-free reference pattern.

The search for a coherent pattern (or lack thereof) in the test material forms the basis for error detection. To accomplish this, an image of the test material must be probed systematically, using the simplest relations possible. From this systematic probing comes the idea of a structuring element, a small pattern which is superimposed against the image in question at each pixel position, forming a modified image based on one of two simple operations, erosion and dilation.

Erosion searches for all exact pattern matches of the image with the structuring element and sets or clears the pixel at the predetermined origin of the structuring element for each comparison made. The effect is to "erode" or shrink all objects in the image. Dilation looks for any conjunction of objects with the structuring element, therefore filling any gaps or holes in the objects.

The application of these simple grayscale morphological techniques proved to be insufficient. While it is possible that a further study of grayscale morphology may yield positive results, the number of calculations required for more complex operations will be prohibitive and would undoubtedly require longer times than design constraints on the inspection unit would allow.

Thus, the results of the investigation of machine vision detection of defects in denim fabric suggest that the line scan system is more effective that the area camera in detecting a variety of defect types. It appears that the techniques employed in this study with the line scan camera can reliably detect all but two of the defects, oil spots and slack ends, investigated in this work. These two accounted for 17% of the 54 defects listed in Appendix A.

VI. COLOR MEASUREMENT SYSTEM

The Hunter Lab SpectraProbe was selected as the color measurement component for the system. This instrument makes non contact reflectance measurements at 77 points in the visible spectrum (5 nm intervals) at a rate of 15 complete measurements per second. The data can be expressed in a variety of color specification systems and directly loaded into a spreadsheet format for subsequent analysis.

The first task involved a survey of manufacturers to determine acceptable color differences between two indigo dyed denim parts that can be sewn together in a garment. Manufacturers use different systems for color specification so all data had to be recalculated so that it could be expressed in the same system. The International CIE system using Light Source C and the 1931 Standard Observer were used as the basis for expressing the color differences. Differences are expressed as differences in lightness (DL), redness-greenness (Da) and yellowness-blueness (Db). Data obtained from three jeans manufacturers and two denim fabric manufacturers are shown below:

DL	Da	Db
±0.45	±0.15	±0.30
±0.50	±1.00	±0.35
±.020	±0.08	±0.20
±0.45	±0.20	±0.20
±0.40	±0.25	±0.25

With the exception of the unusually large Da value of ± 1.00 accepted by one manufacturer, the values are quite reasonable. Eliminating the unrealistically large Da value, average acceptance values of DL = ± 0.40, Da = ± 0.15, and Db = ± 0.25 appear to be the best values to use in determining if two denim parts are an acceptable color match for sewing together in the same garment. None of the manufacturers surveyed was using a calculation of a single color difference value to determine if the shade was acceptable. All indicated that they felt the pass-fail decision should be made on the basis of tolerances in L, a and b and not a single color difference.

The second task involved a determination of the precision of the Hunter Lab SpectraProbe in measuring the L, a and b values of typical denim fabrics. A sample of denim was measured 18 times over a period of one month and the total range of values obtained were:

$$L = \pm 0.23$$
$$a = \pm 0.05$$
$$b = \pm 0.26$$

These ranges are well within the tolerances derived from the data supplied by the jeans and denim fabric manufacturers for fabric that can be sewn into a garment with no shading problems. It would appear therefore that the color measurement system is capable of determining the color of denim fabric with sufficient precision to detect parts that could create shading problems in jeans manufacture.

Samples of utility trousers that were rejected for shading defects were obtained from a military utility trousers manufacturer. These samples were disassembled and the color of the eight major parts determined with the SpectraProbe. The measurement system could easily identify the parts in these shaded trousers that were defective. The differences noted in the L, a and b values for these shaded parts were consistent with the tolerances previously established from data supplied by the jeans and denim fabric manufacturers.

The colors of samples from several hundred rolls of fabric for Navy denim trousers have been measured to determine the variability that currently exists in this product. Excessive differences in the color from roll-to-roll could create significant problems in requiring cutting of large numbers of parts to replace defective parts removed in the defect removal process. The results of these experiments suggest that current color production control procedures produce most rolls with color tolerance within the limits required for color match in garments.

VII. DEFECT DETECTION WORKCELL

A fabric defect detection workstation was designed, for automatic inspection of cut parts. As briefly mentioned before the workstation consists of five components--a pick and place device to select parts from a stack and place them individually on a conveyor belt, a conveyer belt transport system to move parts to the various inspection stations, a machine vision system (including both line and area camera systems) to inspect parts for fabric defects, a non contact color measurement system to precisely measure the color of each part, and a take-off device that will reject defective parts and place acceptable parts in a configuration suitable for input to an automated sewing workstation. The system will be under the overall control of a microcomputer for integration of the operation of the various components in the system and for analysis of the collected data to permit decision regarding the acceptability of each part. The system can also calculate the area and perimeter of each part to determine if the part has been properly cut. Thus, the workstation should insure that only defect free, color matched, and properly cut parts will enter the assembly operations with the parts already configured to feed an automated sewing workstation. Our concept for a workcell to accomplish the above mentioned tasks is illustrated in Figure 6.

Denim fabric used for manufacture of Navy Men's Utility Trousers was selected for demonstration of the cut part inspection system. The manufacturing process for this product is typical of the very large segment of the apparel industry involved in production of denim garments. The Navy trouser has eleven parts (left and right front and back leg panels, 4 patch pockets, left and right fly, waistband). The prototype workstation was designed to inspect the leg panels and the pockets. The design objectives were an inspection time of four seconds for a leg panel and one second for a pocket (approximately 20 seconds inspection time per garment) with a positive detection of over 50% of the most common defects found in denim fabric. The goal of the inspection workstation was a minimum of a 50% reduction in seconds in finished garments due to fabric defects and shading problems. It was felt that such a workstation would make a very attractive contribution to reduction of costs due to fabric defects in finished garments.

Equipment selected for initial study and evaluation and possible inclusion in the proof-of-concept model of the workstation is shown in Table 5.

Part Pick-and-Place	Jet Sew
Machine Vision Unit	IRI SVP Area Camera
	EG&G Line Camera
Color Measurement	Hunter SpectraProbe
Conveyor System	In-house Design
Take-off Unit	In-house Design

Table 5 Cut part inspection unit components.

A block diagram illustrating the system is shown in Figure 7.

VIII. INTEGRATION OF AUTOMATIC DEFECT DETECTION WORKCELL

A. Lighting and Optics

It has been reported that approximately seventy different flaws have been identified in denim fabric [10]. Fortunately, many of these defects are very uncommon. Our studies, have shown that five defects accounted for 65% of the observed flaws. These along with nine of the more common defects were chosen for detection in this workcell.

As discussed earlier parts of the lighting and optical system interact to determine the final quality of the image. Some of these parameters include the light source, the properties of the material being illuminated, as well as the properties of the sensors in the cameras. From earlier tests, the orientation illustrated in Figure 8 was shown to be most effective for both enhanced contrast and consistency using a Xenon light source.

B. Integration of Machine Vision Systems

1. Area Scan System

Previous work [10] has shown that area scan vision systems could be used for defect detection in denim but needed processing time on the order of 10 to 12 seconds to conduct the inspection of about a 6x6 inch area. We examined two techniques using the area scan system [13] and found that on the whole the line scan system was more effective for the defects being considered. We will go into more detail on the techniques below. The area scam system was used for doing the size determination , however.

2. Line Scan System

In order that we might obtain improved speed, consistency and ease of integration we changed line scan systems from the Digital Design System used in our initial tests to a PC based system from EG&G Reticon. The tools on this were not the same as those on the original system and as a result we had to write additional software to complete the transfer of the algorithms and the workcell integration.

A key element of the technique outlined earlier is the position of the thresholds along with a mechanism for filtering extraneous information in the acquired image. This is even more important when the large variety of denim products are considered, as many of these will require different thresholds. In previous sections a trial and error technique for configuring the optics and lighting system and defining the thresholds was presented. A more systematic technique will now be described.

A photograph of a typical area of denim is shown in Figure 9. A line image across this sample is displayed in Figure 10. The transitions of the material have a dynamic range of about 30 gray levels.

Denim is woven using alternating light and dark fibers at a frequency of approximately 40 to 50 picks/inch. The power spectrum of the above sample is shown is Figure 11 and indicates that the peak power lies at about 26 samples/inch significantly less than the weave frequency. This might seem surprising, but on further observation, it is noticed that because of overlapping and intertwining of the fibers used in weaving the texture of the material did not visually occur at the weave rate. In addition the majority of the defects manifested themselves as high intensity spots with sizes typically larger than the size of the yarn.

Another observation was that defects would typically be lost in the noise as shown in Figure 12. It was decided that filtering and smoothing of the data would be appropriate up to the point where most of the information in the signal could still be obtained. This was accomplished by an optical filtering technique achieved by defocusing the camera to obtain the same shown in Figures 12 with power spectrum as shown in Figure 13. It should be noted that the defocusing (low pass filtered) retained the peak at approximately 26 samples/inch, thereby retaining the most of the image information. This operation also reduced the dynamic range of the data to about 10 gray level. Through experimentation it was found that thresholds of approximately one standard deviation above and below the mean was effective for finding defects, using our algorithms on the filtered images.

Table 6 shows the results obtained in a detection test of 30 fabric defects where sample orientation and position were carefully controlled.

Orientation can play a role when the defect in question is directed along a particular axis, such as the Sloughed Filling or Slack End defects. Because the line scan system is effectively one-dimensional, these defects may appear in certain orientations to be nothing more than normal fabric. Presently, each defect must be aligned to closely coincide with the orientation of the scan line in order to provide reliable detection. To overcome this limitation, a two-dimensional picture may need to be constructed by storing several successive line scans for periodic analysis or buffers might be maintained on several potential defects as each individual line is scanned.

DEFECT NAME	FALSE HITS	CORRECT HITS
Accum, Kinks	No	Yes
Oil Spot	Yes	No
Slack End	No	Yes
Seam	No	Yes
Harness Breakdown	No	Yes
Slack End	No	Yes
Jerked In Filling	No	Yes
Dyeing Defect	No	Yes
Slack End	No	No
Slub	No	Yes
End Out (Wrap)	No	Yes
Stub (Fill)	No	Yes
Broken Pick	No	Yes
Sloughed Filling	No	Yes
Dyeing Defect	No	Yes
Slack End	No	Yes
Slack End	No	No
Broken Pick	No	Yes
Slub	Yes	Yes
Slub (Wrap)	Yes	Yes
Slub	No	Yes
End Out	No	Yes
Oil Spot	Yes	No
Sloughed Filling	No	Yes
Harness Breakdown	Yes	Yes
Finishing Spot	No	Yes
End Out	No	Yes
Slack End	No	Yes
Woven Waste	No	Yes
Slack Filling	No	Yes

Table 6 Results of defect detection trail.

The difference in average intensity does not vary significantly from one sample to another, but a few samples differ greatly from the norm and even the small differences between the majority of samples can cause errors. All image analysis techniques require a defect-free reference image or model from which to set constraints, and consistency in overall intensity of any material being analyzed is crucial to the success of these techniques. It is assumed, however, that individual pieces put together into a single garment will be from the same roll number and sufficiently close in average gray-level intensity.

IX. WORKCELL PERFORMANCE

A proof of concept workcell was built and was demonstrated at the Third Annual Academic Apparel Research Conference in Atlanta in April 1992. Pictures of the system and its components are shown in Figures 16 through 19.

In order not to miss a defect that was approximately a pick in size, we were able to achieve an inspection speed of approximately one inch/sec. using a camera resolution of 160 samples/inch. Most defects are bigger than one pick and using defects about 2.5 to 3 inches in length (hand generated) we were able to run the cell at approximately four inches per second. Our desired speed was 12 inches per second, thus, we were able to run at approximately a third of the target value.

Part of our speed limitation was due to the fact that we were utilizing a PC based system for the line scan camera. Approximately 50% of the inspection time was actually spent transferring data across the PC bus. In addition the algorithm implementation could be greatly optimized in a more flexible processing environment. With these improvements 12 inches/second would be achievable. Periodically we also observed some noisy line scans from the camera. We suspected this to be due to malfunctioning hardware.

X. RECOMMENDATIONS

The final workcell was 16 feet long by 5 feet at its widest point. This is probably bigger than could be accommodated easily in most manufacturing facilities considering its function. We believe however, that the system could be integrated to provide the same functionality in a machine the size of the JetSew picker. This would require minuraturizing the color measuring head and the line scan system and its peripheral devices. The technology to design and assemble these components exist, and a machine such as this would be quite feasible.

In developing the algorithms we used a material that was fairly uniform as opposed to patterned. We showed that it was possible to see many of the common defects in this type of material. Other techniques for defect detection on this and other kinds of material should also be investigated. Promising technologies include the use of Neural Nets in which the system is trained to recognize good and defective material. Research in the use of this technology is showing promise in many areas that seemed impossible previously.

XI. SUMMARY

The results of our work indicate that defect detection in denim is possible with available technology. Problem areas include inconsistent image acquisition and lack of processing capability on some existing boards. The technology for including more capability already exists in other systems and is really a problem of integration. Another consideration is tailoring the algorithms for different types of denim. One manufacturer, for example, makes 60 different types of denim. The techniques outlined above could also be used to determine thresholds and optimizing filters.

The present work on the important machine vision and color measurement components of the automatic fabric defect detection system suggest that the existing equipment can effectively detect the majority of fabric and color flaws that are responsible for defects in finished garments. The proof-of-concept model of the cut part defect detection workstation was designed, built and demonstrated at the Georgia Tech-Southern Tech Apparel Manufacturing Technology Center in 1992.

XII. REFERENCES

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XIII. FIGURES

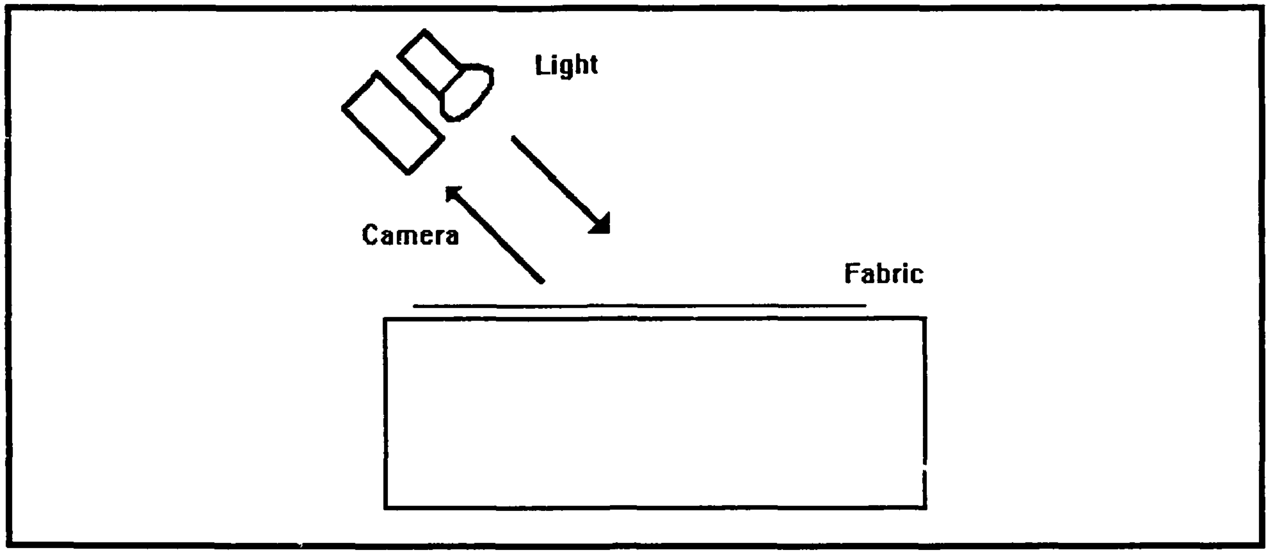

Figure 1 Lighting configuration 1.

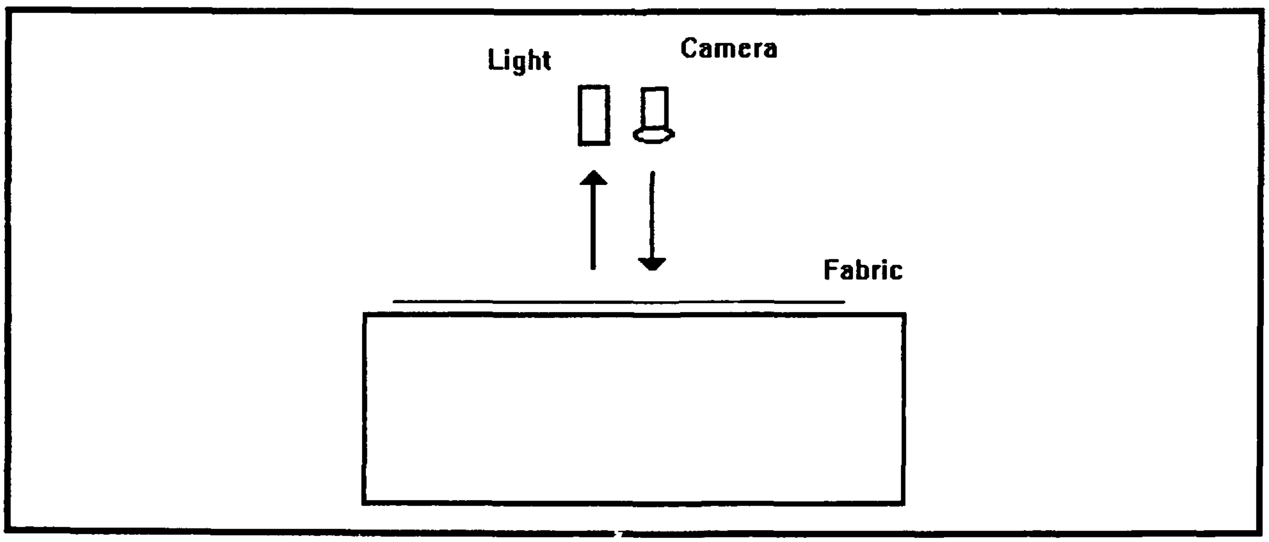

Figure 2 Lighting configuration 2.

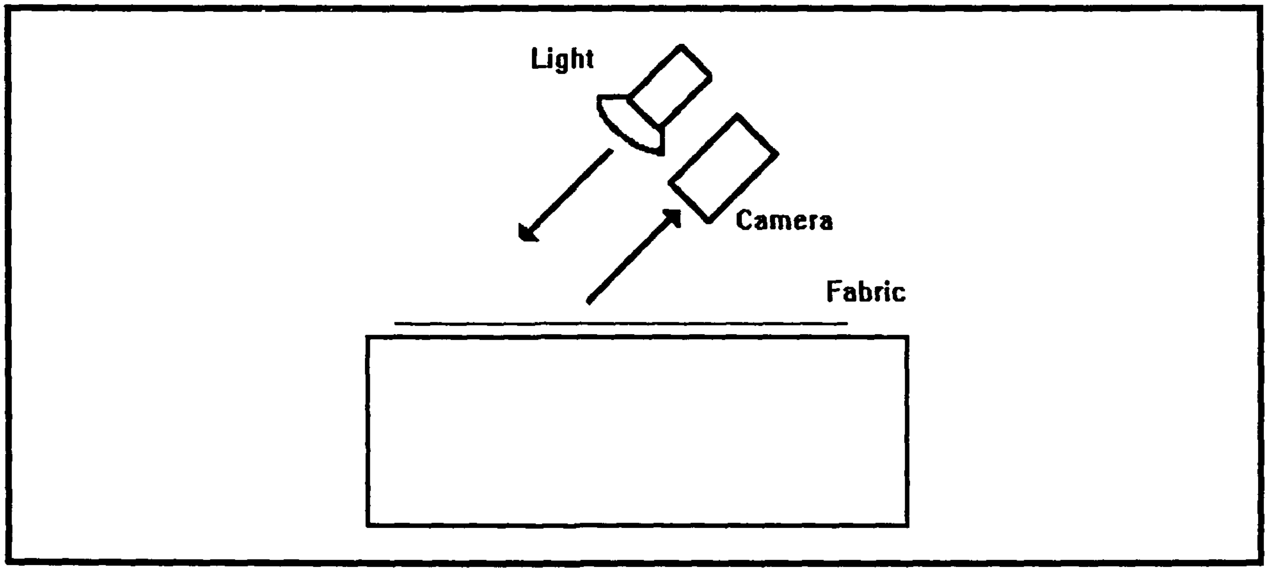

Figure 3 Lighting configuration 3.

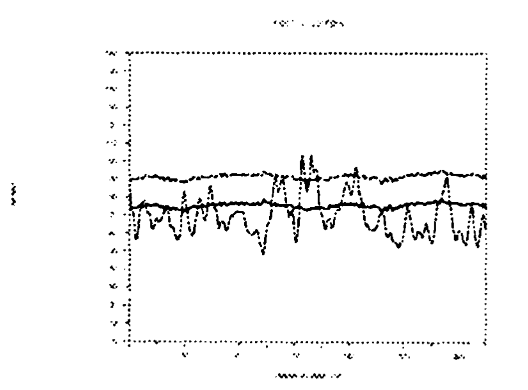

Figure 4 Line scan of good denim.

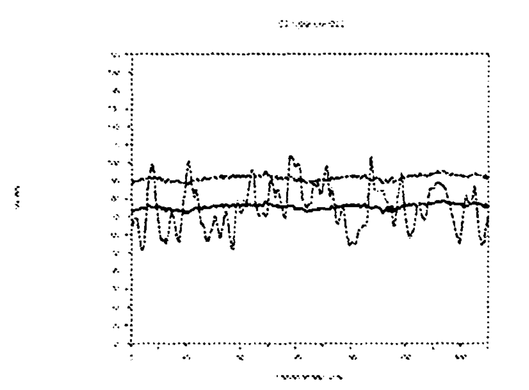

Figure 5 Line scan of denim with defects.

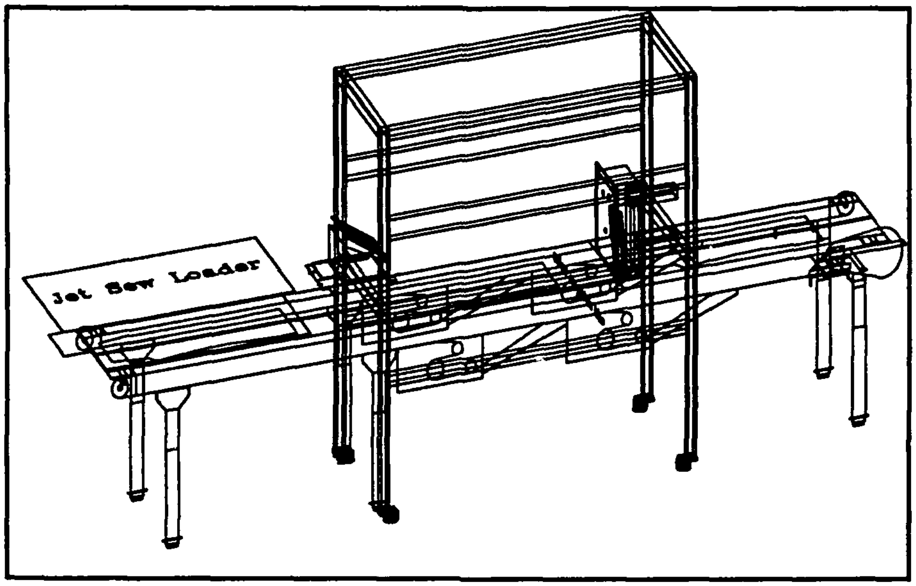

Figure 6 Assembly drawing of workcell.

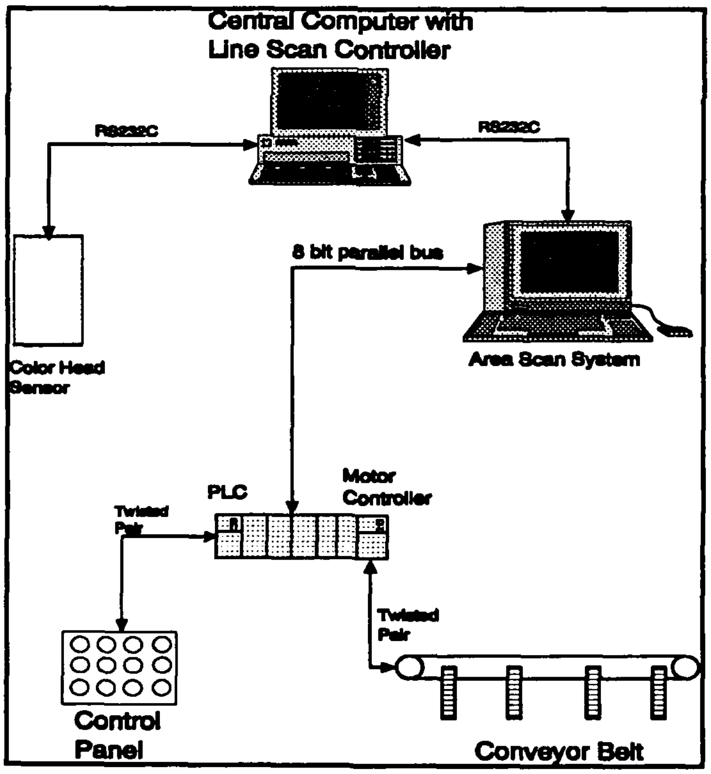

Figure 7 Diagram of cell controller.

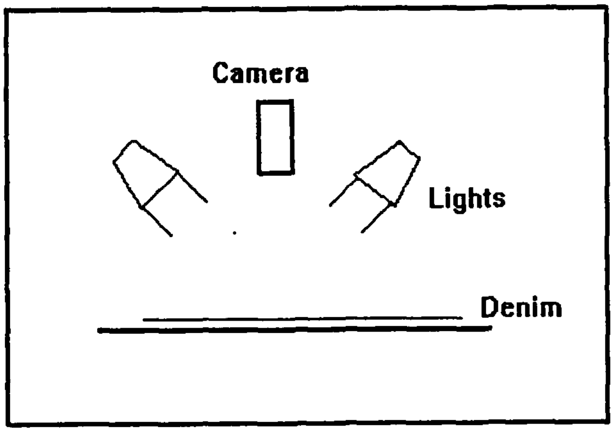

Figure 8 Lighting configuration for demonstration work cell.

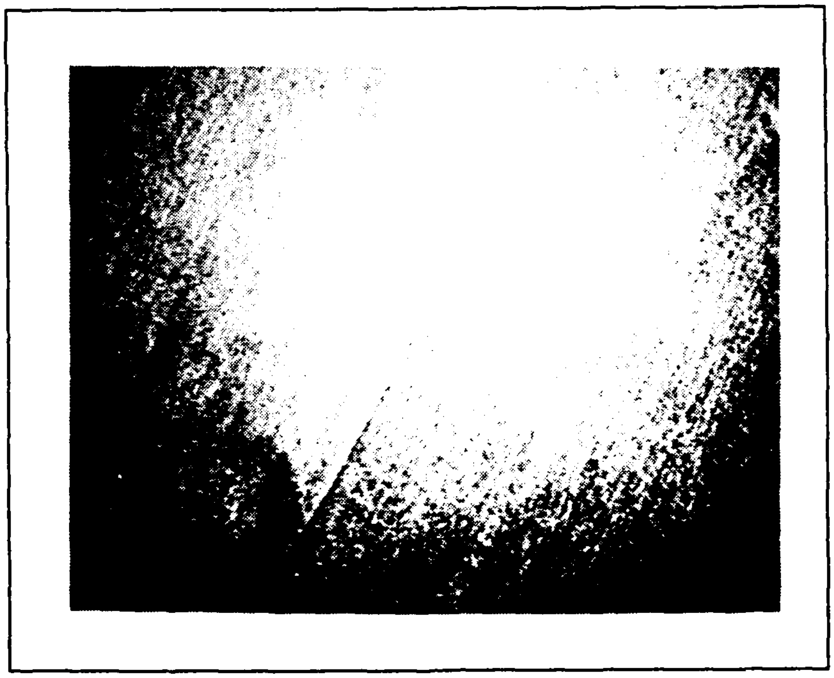

Figure 9 Typical denim sample.

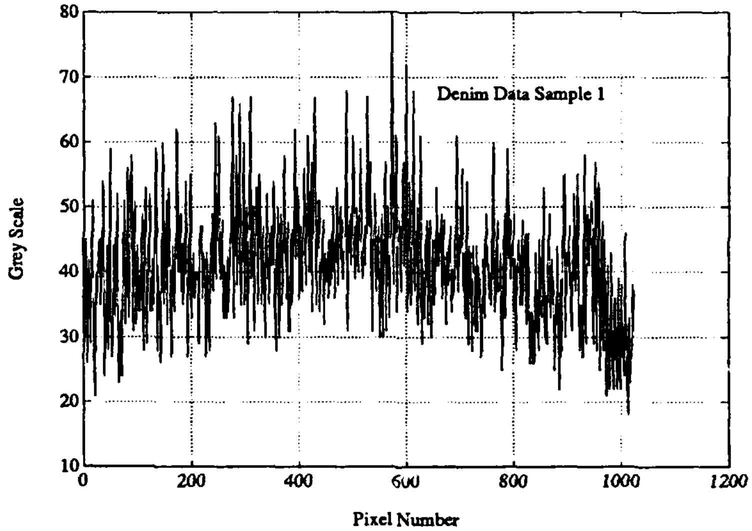

Figure 10 Raw line data image sample 1.

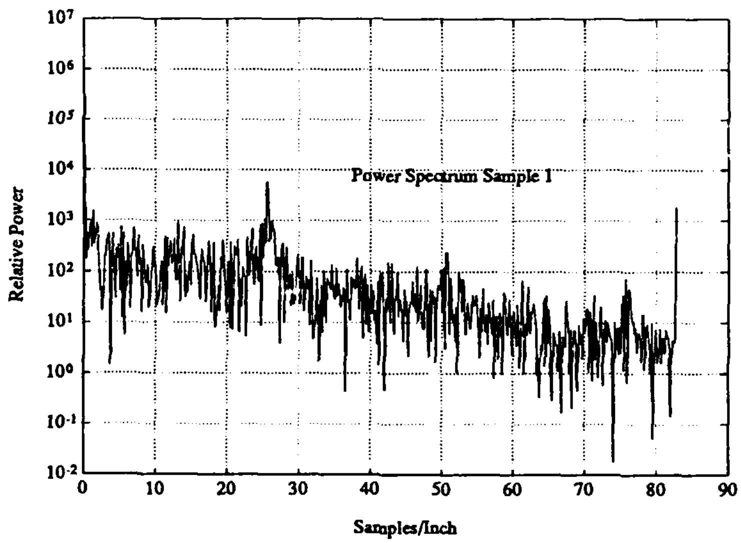

Figure 11 Power spectrum response sample 1.

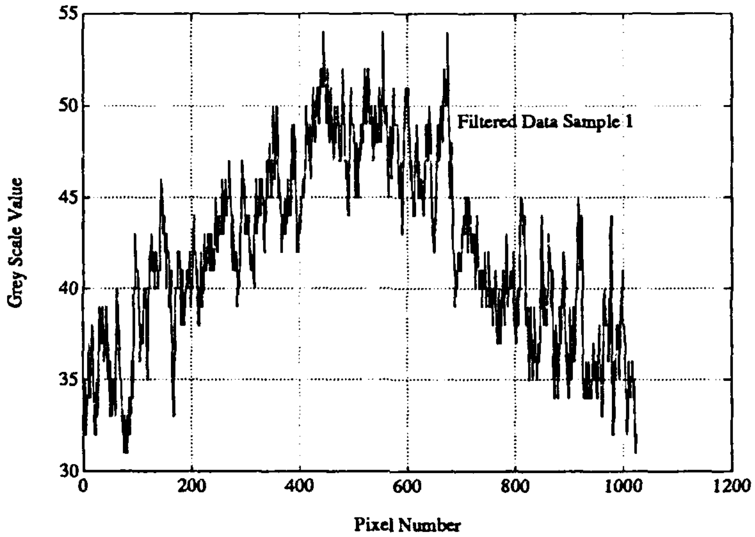

Figure 12   Filtered data sample 1.

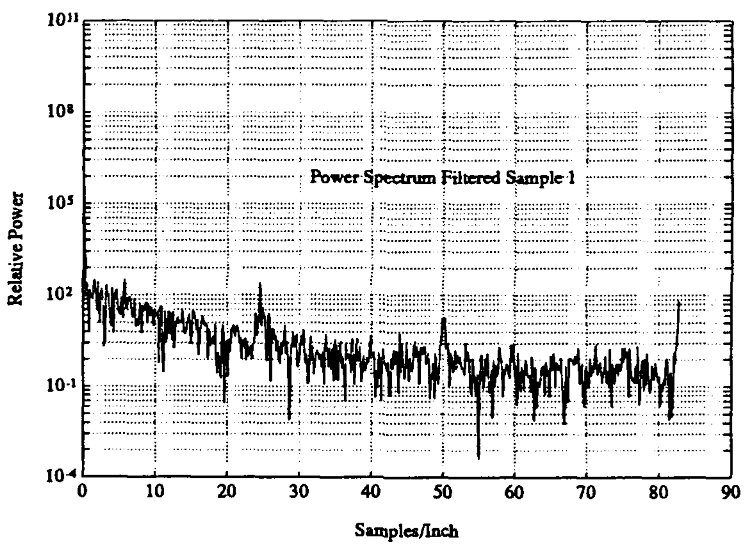

Figure 13   Power spectrum filtered sample 1.

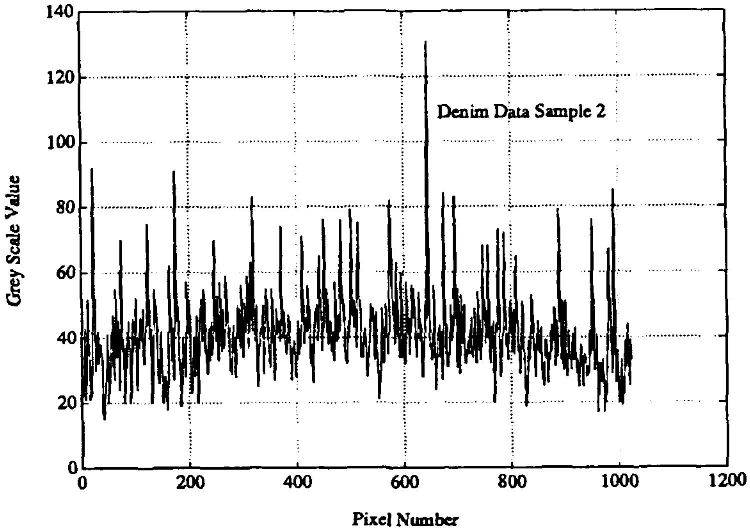

Figure 14 Spatial data denim sample 2.

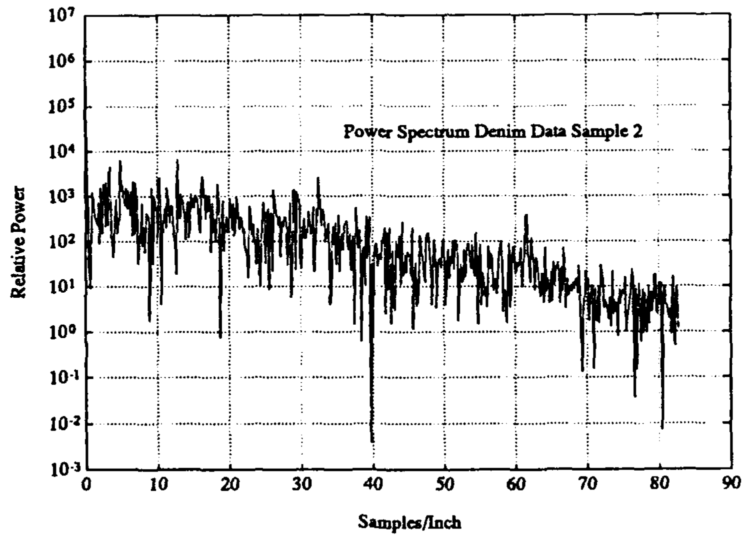

Figure 15 Power spectrum of sample 2.

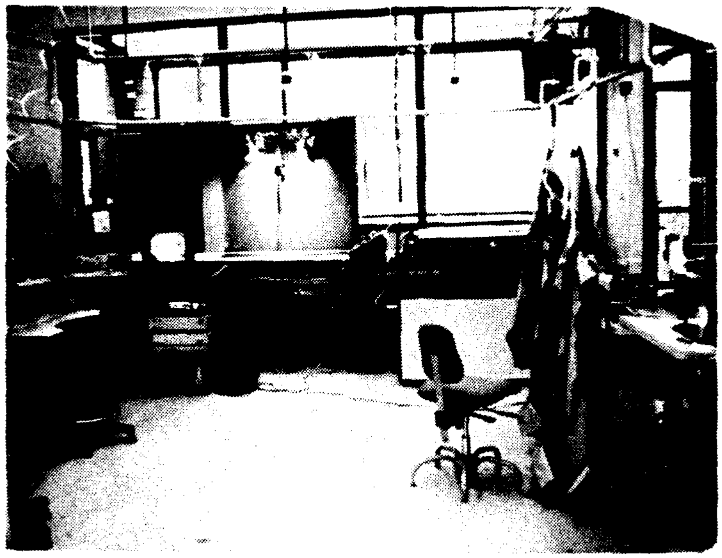

Figure 16 Photograph of workcell.

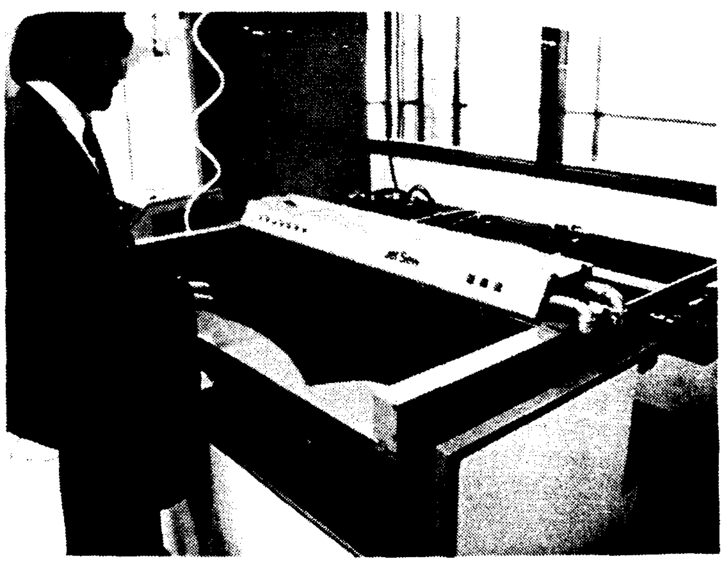

Figure 17 JetSew picker.

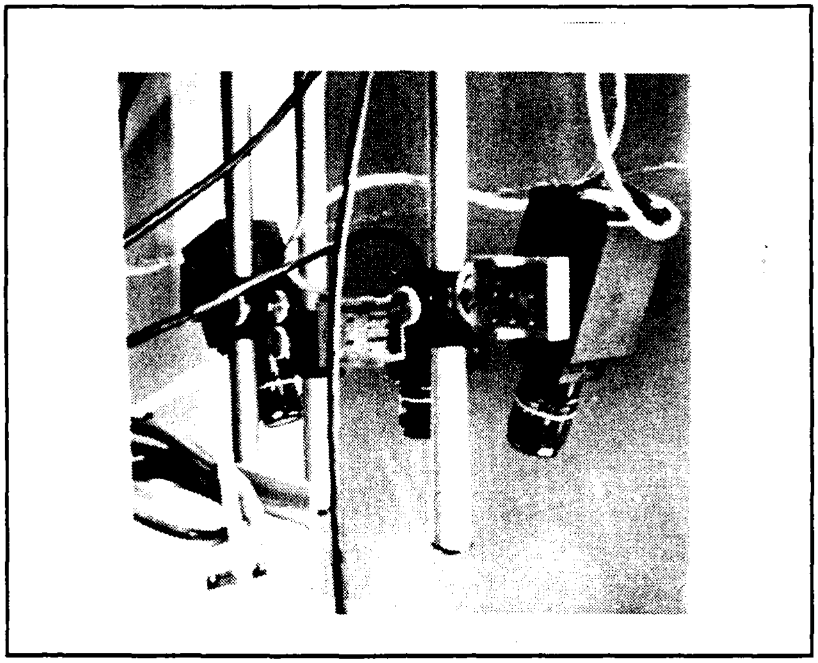

Figure 18 Line scan camera and lights.

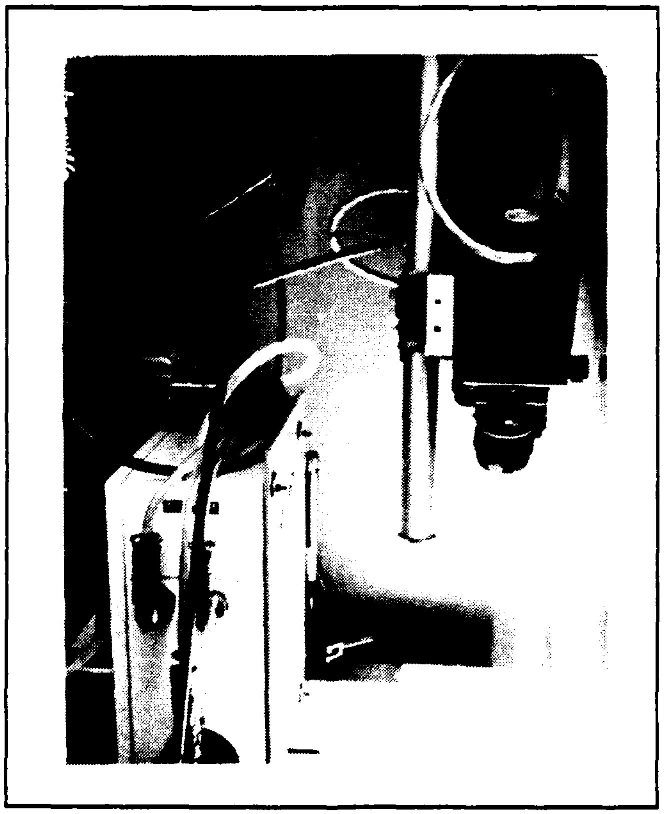

Figure 19 Color measuring head.

APPENDIX A
ANALYSIS OF DENIM FABRIC DEFECTS
JEAN MANUFACTURING PLANT STUDY
NOVEMBER 1989

CUT NO IDENTIFICATIO N	ROLL ON IDENTIFICATION	DEFECT NO	DEFECT
409	513888	1	Broken Pick (Unremoved)
409	513788	1	Harness Breakdown
409	513788	2	Slack End (Warp)
409	513788	3	Slub (Warp)
409	513788	4	Jerked-In Filling
409	513788	5	Dyeing Defect (Warp)
409	513788	7	Slack End (Warp)
409	513792	1	Slub (Filling)
409	513792	2	End Out (Wrap)
409	513792	3	Slub (Filling)
409	513792	47	Dyeing Defect (Warp)
409	513792	5	Dyeing Defect (Warp)
409	513792	6	Dyeing Defect (Warp)
409	513782	2	Broken Pick
409	513782	3	Slub (Filling)
409	513782	4	Seam
409	513782	5	Seam
409	513782	6	Slack End (Warp)
410	523080	1	End Out (Wrap)
410	523080	2	Slack End (2 in Warp)
410	525123	1	Slack End (Warp)
410	525123	2	Seam
410	519551	1	Harness Breakdown
410	519551	2	End Out (Warp)
410	519551	3	End Out (Warp)
410	519551	4	Seam
410	519551	5	Oil Spot
410	518441	2	Broken Pick
410	518441	3	Slub
410	525579	1	Woven-In Waste
410	525579	2	Slack Filling (Selvage)
411	518441	1	Slack End (Warp)
411	520438	2	Sloughed Filling
411	520438	5	Seam
411	520438	6	Sloughed Filling

411	520438	7	Seam
411	520438	8	Sloughed Filling
411	520438	9	Skew (Bias)
411	520438	10	Harness Breakdown
411	518396	4	Sloughed Filling
411	518396	6	Sloughed Filling
411	518396	7	Sloughed Filling
411	518415	2	Slack End (Warp)
411	519531	1	Harness Breakdown
412	521692	1	Seams
412	514920	1	Slack End (Warp)
412	514920	2	Finishing Streak
412	516223	1	Sloughed Filling
412	516223	2	Dyeing Defect (Warp)
412	516223	3	Finishing Streak
412	518472	1	Slub (Warp)
412	521692	2	Finishing Spot
412	521692	3	Slub (Filling)
412	521692	4	Broken Pick

TOTAL DEFECTS BY TYPE		
Broken Picks	4	7%
Slack Ends	8	15%
Slubs	7	13%
Dyeing Defects	5	9%
Seam	7	13%
Harness Breakdown	3	6%
Jerked-In Filling	1	2%
End Out (Warp)	4	7%
Oil Spots	1	2%
Woven-In Waste	1	2%
Slack Filling (Sel.)	1	2%
Sloughed Filling	8	15%
Skewed Fabric (Bias)	1	2%
Finishing Streaks	3	6%
TOTAL	**54**	